ULB-TH/05-14.

Leptogenesis and Dark Matter related ?

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February 2, 2008

Abstract

We investigate the possibility that dark matter and the baryon asymmetry of the Universe are generated by the same mechanism, following an idea initially proposed by V.A. Kuzmin and recently discussed by R. Kitano and I. Low. In our model, based on a left-right extension of the Standard Model, the baryon asymmetry is generated through leptogenesis and dark matter is made of relic stable right-handed neutrinos with mass $\sim$ few GeV. Constraints on the model imply that this form of dark matter would unfortunately escape detection.

1 Introduction

According to the Concordance Model, ordinary matter in the form of baryons represents only $\Omega_B \approx 5\%$ of the energy density of the Universe. The rest is apparently shared between Dark Matter and Dark Energy, with $\Omega_{DM} \approx 25\ \%$ and $\Omega_{DE} \approx 70\ \%$ respectively [1]. Dark energy is supposed to be responsible for the accelerated expansion of the Universe but otherwise its true nature eludes us. The dark matter problem is almost mundane in comparison. We have a plethora of well-motivated and well-understood particle physics candidates, the most acclaimed currently being a neutralino, and we know of the existence of at least one component of dark matter, in the form of light neutrinos.

In the present paper we would like to address a nagging puzzle related to dark matter. This is the apparently coincidental fact that the energy density in baryons and that of dark matter are nearly the same

$$\Omega_b/\Omega_{dm} \approx 1/5. \tag{1}$$

This similitude is generally not addressed by scenarios predicting the existence of dark matter, nor a fortiori by those concerned with baryogenesis. Yet, although

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the ratio (1) is constant today this was not the case for all the history of the universe and, at least for conventional dark matter and baryon matter generation mechanisms, (1) is a puzzle.

By way of introduction, it is instructive to have a look at leptogenesis, the simplest mechanism which establishes a relation between dark matter (in the form of neutrinos) and the abundance of baryons. Leptogenesis fixes the ratio of baryon to cosmic background neutrino number densities (assuming the neutrino asymmetry itself is negligible) and requires the neutrinos to be light Majorana particles. It is well appreciated that neutrinos are too light to be the dominant form of dark matter but this is not our main concern here. More to the point is the fact that the constraints from leptogenesis on neutrinos masses are rather loose (the range $0.001 \lesssim m_\nu \lesssim 0.1$ eV is claimed in [2] but the range could be much broader, see [3]). Yet $3 \lesssim \Omega_b/\Omega_\nu \lesssim 70$, where the lower bound comes from large scales structure formation ($m_\nu \leq 0.7eV$) [1] while the upper bounds comes from neutrino oscillations ($m_\nu \geq 0.03eV$) [4]. This is surprising, since leptogenesis has nothing to say about the baryon to neutrino mass ratio. Yet the ratio of baryon to neutrino energy densities are almost similar.

The above discussion illustrate a shortcoming of most attempts (including ours) to explain (1) *i.e.* that one has to understand both the particle number density ratio and the particle mass ratio. A most straightforward explanation could be that dark matter is made of antibaryons, albeit of course of an exotic, neutral and stable form, that could compensate the baryon number of ordinary matter. This is not in contradiction with nucleosynthesis or CMB fluctuations, since these observations constrain only the number of protons and neutrons (and their bound states). In such a scheme one would automatically get (1) of $\mathcal{O}(1)$ with the mass of dark and visible matter related to the scale of QCD. Of course we know too much about strong interactions and it seems difficult to make this idea consistent with observations. (There has been however and interesting recent attempt in this direction [5].)[1]

This lengthly introduction brings us to the much less ambitious path that will be ours. The main idea goes back to old works of Barr *et al* [7] and Kaplan [8] and more recent inputs of Kuzmin [9] and Kitano and Low [10, 11]. This approach allows to fix the ratio of particle densities. The mass of dark matter particles then comes as a prediction to be tested.

2 Matter Genesis

The basic setup assumes that there is an asymmetry in the dark sector related to the baryon asymmetry of the universe. Both baryon matter and dark matter then owe their existence to a single mechanism, a sort of matter genesis.

The different existing scenarios (see [5, 7, 8, 9, 10, 11, 12]) differ in the

[1] Yet another possibility would be to hide ordinary antibaryons into primordial black holes but this idea raises further issues, not the least being to find a mechanism responsible for the separation of matter and anti-matter. Also, primordial black hole have problems of their own (see [6] for a recent discussion).

implementation of this very idea, however there are some similarities in the conditions to be satisfied. Here we outline the version of [10] that inspired us. By necessity, there is a dark sector, composed of a set of new particles. The visible sector, which consists of, among other things, baryons, and the dark sector communicate with each other but the interactions are suppressed at low energies. The lightest of these particles is protected from decay by some discrete symmetry, analogous to R-parity. This lightest particle cannot be produced thermally in the Universe. If it were, the tiny asymmetry in the dark sector would be drowned by numbers. This last condition motivates the introduction of a particle in the dark sector that we call the messenger particle. This particle is strongly interacting and in thermal equilibrium in the early universe. Because it is strongly interacting, it stays in thermal equilibrium even when it becomes non-relativistic and that messengers and their antiparticles begin to annihilate. The situation in the dark sector at this point is like that for ordinary baryons in the visible sector. Baryons and messengers both survive to annihilation thanks to a tiny asymmetry in their respective sector. In the visible sector, neutrons decay into protons and the chain ends. In the dark sector, the messengers decay into the lightest stable particle, that should better be electrically neutral.

There are presumably many possible concrete realization of this scenario. Ours differs from those pre-existing in the literature on the following points. First our prejudice will be that the mechanism responsible for matter genesis is leptogenesis. Then dark matter will then be made of light, $m \sim$ few GeV, right-handed Majorana neutrinos. Last our model is based on an extension of the Standard Model (SM) which has been proposed for other purposes. The model is very constrained and, we agree, not the nicest model one would dream of. However we believe that there are some lessons to be drawn from it.

As we shall discuss, the main drawback of this model and its siblings, will be that, at the end of the day, it does not look very natural. Then, the mass of dark matter particles will come in as a constraint, not a prediction, but this was to be anticipated from the discussion in the introduction. Finally, the kind of dark matter of the type we consider would escape all attempts of detection. The messenger particle could be observed in high energy colliders, since it is a strongly interacting particle, similar to a (very very) heavy quark.

3 The Model

We have chosen to concentrate on a specific extension of the Standard Model that was proposed many years ago in [13] as an alternative to the SM way of giving mass to the quarks and leptons and is known in the literature as the "universal see-saw model". The gauge group is $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. The left and right-handed quarks $Q_{R,L}$ and leptons $L_{R,L}$ are respectively $SU(2)_L$ and $SU(2)_R$ doublets and, in the simplest framework, there are two Brout-Englert-Higgs (BEH) doublets,

$$\phi_L \sim (2, 1, 1)$$

and

$$\phi_R \sim (1,2,1).$$

To give mass to the quarks and leptons, one introduces a set of $SU(2)$ singlet Weyl fermions and a Majorana fermion N:

$$U \sim (1,1,4/3) \quad D \sim (1,1,-2/3) \quad E \sim (1,1,-2) \quad N \sim (1,1,0).$$

Note the unusual $B-L$ charge assignment of these fields. The BEH bosons, for instance, have a non-zero $B-L$ charge, and there is a completely neutral field N. The latter will play the role of the heavy Majorana particle, analogous to the heavy right-handed Majorana neutrinos in standard leptogenesis scenarios.

This model looks nice but, unfortunately, we will need to complicate it a bit further. In particular we need to implement a discrete symmetry to protect the dark sector. We follow in that an old proposal of Babu *et al* [14]. First we add two BEH scalars in the adjoint, whose purpose will become clear later on:

$$\Delta_L \sim (3,1,2) \qquad\qquad \Delta_R \sim (1,3,2).$$

Then we impose the following Z_4 symmetry

$$\begin{array}{lll} D_L \to -D_L & Q_R \to iQ_R & L_R \to -iL_R \\ \phi_R \to -i\phi_R & \Delta_R \to -\Delta_R & N_R \to -N_R, \end{array}$$

all other fields transforming trivially under Z_4. The first effect of this symmetry is to forbid a Dirac mass term for the D field and Yukawa couplings to the N (would be neutrino Dirac mass terms). The allowed Yukawa couplings and mass terms then take the form

$$\begin{aligned} \mathcal{L}_y &= h_d \bar{Q}_L \phi_L D_R + h_u \bar{Q}_L \tilde{\phi}_L U_R + h_e \bar{L}_L \phi_L E_R \\ &+ \lambda L_L^T C^{-1} \tau_2 \vec{\tau} \vec{\Delta}_L L_L \\ &+ M_U \bar{U}_L U_R + M_E \bar{E}_L E_R + M_N \overline{N^c} N \\ &+ (L \leftrightarrow R) + h.c.. \end{aligned} \tag{2}$$

This seems utterly complicated but the interesting things come with symmetry breaking. Let us write $v_{L,R}$ the *vev* of $\phi_{L,R}$ and $\kappa_{L,R}$ the *vev* of the triplets. Then the neutrino fields are all pure Majorana

$$\lambda\, \kappa_L\, \overline{\nu_L^c} \nu_L \;+ \lambda'\, \kappa_R\, \overline{\nu_R^c} \nu_R \;+ M_N\, \overline{N^c} N.$$

The up-like quarks and charged leptons get their mass from mixing with the heavy Dirac singlets

$$(\bar{f} \quad \bar{F}) \begin{pmatrix} 0 & h v_L \\ h v_R & M \end{pmatrix} \begin{pmatrix} f \\ F \end{pmatrix} \sim \frac{h^2 v_l v_R}{M} \bar{f} f + M \bar{F} F,$$

where $f = e, u$ and $F = U, E$ thus following the usual "universal see-saw" pattern.

The twist is in the down-like quark sector. Because there is no Dirac mass term for the D field, mixing is maximal

$$h_d\, v_L\; \bar{d}_L D_R + h_d\, v_R\; \bar{D}_L d_R + h.c. = \; h_d\, v_L \bar{d}' d' + h_d\, v_R\; \bar{D}' D',$$

and the role of the "light" and "heavy" right-handed down-like fields are so to speak exchanged. The D' particle, which couples to $SU(2)_R$ gauge bosons, will be our strongly interacting messenger particle. It is supposed to be lighter than the singlet fermions.

The ν_R will get their mass from the *vev* of the $SU(2)_R$ adjoint scalar field. In the sequel, we assume that $m_{\nu_R} \ll m_{D'} \ll M_N$. (The mass of the U and E are not very much constrained. We will only request that the E, U disappear before the electroweak phase transition.)

Finally, after left-right symmetry breaking, there is a residual Z_2 symmetry. The heavy Majorana field N, the heavy down-like quark D', the Majorana neutrino ν_R as well as the charged boson fields $W_R^{\pm}$, $\phi_R^{\pm}$ and $\Delta_R^{\pm}$ are all odd under Z_2. All together, they constitute the dark sector of our model.

3.1 Initial B-L asymmetry

We will assume that the initial $B-L$ asymmetry is provided by the out-of-equilibrium, CP violating decay of the heavy singlet Majorana fields N. For definiteness, we assume that decay takes place after left-right symmetry breaking. The abundance of N's could be thermal or they could be created during reheating after inflation. Note that these fields are odd under the Z_2 symmetry and are thus the grandfather of our dark matter particles. The decay process is supposed to be dictated by higher scale interactions but we can parameterize it by dimension six effective operators like

$$\frac{1}{\Lambda^2} \bar{N} E \bar{D} U + h.c.,$$

where the D particle is the mass eigenstate, odd under the Z_2 symmetry (since there should be no confusion at this point, we drop the prime on the D). Assuming CP violation, these decay processes may sequestrate a $B-L$ asymmetry between the dark and visible sectors

$$n_{B-L}^{vis} = -n_{B-L}^{dark} = -q_{B-L}^{D}(n_D - n_{\bar{D}}),$$

where

$$n_D - n_{\bar{D}} = n_{\bar{U}} - n_U = n_{\bar{E}} - n_E = \epsilon\, n_N,$$

with

$$\epsilon = (\Gamma_{N \to \bar{E}\bar{U}D} - \Gamma_{N \to E\bar{D}U})/\Gamma_N.$$

3.2 Annihilation of messenger particles

After sequestration of a $B-L$ asymmetry in the dark sector, the Universe contains U, E and D particles on top of the usual Standard Model fermions.

In the visible sector, the E and U are in thermal and chemical equilibrium with the Standard Model fermions, and all together they carry a Z_2-even $B-L$ asymmetry. Eventually, we will require the E and U disappears through annihilation and decay before the electroweak phase transition, leaving only SM degrees of freedom behind. As in standard leptogenesis scenarios, baryon number violating processes that are in equilibrium give birth to a non-zero baryon asymmetry

$$n_B = C\, n^{vis}_{B-L} = -C q^D_{B-L}(n_D - n_{\bar{D}}). \tag{3}$$

The constant of proportionality $C = 25/79$ is calculated in the standard way [15], taking into account that the $B-L$ charge is shared between the visible and the dark sector.

In the dark sector, the messenger particles D carry a Z_2-odd $B-L$ asymmetry. They are heavy, $M_D \sim v_R$, strongly interacting particles and when the temperature of the universe drops below their mass, they annihilate into light quarks but a small asymmetry survives

$$n_D - n_{\bar{D}} \approx n_D \approx \epsilon n_N.$$

It is crucial that we require that there are essentially no ν_R in the universe at this level since we want to obtain a relation between the baryon asymmetry and the density of dark matter. As we will see in section 3.4, this condition constrains the scale of left-right symmetry breaking.

It is also crucial that the messenger particles are strongly interacting so as to leave only the asymmetry as a remnant.

3.3 Decay of messengers into ν_R

The dominant D decay channel is

$$D \to u + e + \nu_R^c,$$

through the exchange of a W_R. If the messenger particles were to decay before the electroweak phase transition, baryon number violating processes in equilibrium would completely erase the asymmetry (3). Indeed the ν_R carry no $B-L$ charge in our framework and all the $B-L$ that was sequestrated in the dark sector is released in the u and e degrees of freedom.

If D decay takes place after electroweak symmetry breaking, the final B asymmetry is given by (3) plus the contribution from the D decay into baryons

$$n_B^{fin} = \left(q_B^u - \frac{25}{79} q^D_{B-L} \right) n_D. \tag{4}$$

The density of dark matter is simply equal to

$$n_{dm} = n_{\nu_R} = n_D.$$

Taking the ratio we obtain

$$\frac{\Omega_B}{\Omega_{DM}} = \left(q_B^u - \frac{25}{79} q_{B-L} \right) \frac{m_b}{m_{\nu_R}} \approx 0.5 \frac{m_b}{m_{\nu_R}},$$

which implies that $m_{\nu_R} \approx 3\, GeV$. As expected, the mass of the dark matter particle is of order of the proton mass.

This scenario, the main features of which are summarized in Figure 1, is quite involved. The main element is that a $B-L$ asymmetry is sequestrated in a sector insensitive to $B+L$ violating processes, at least as long as they are active, and is eventually released. In the present model, this is possible thanks to an exact discrete symmetry which differentiate the dark and the visible sector.

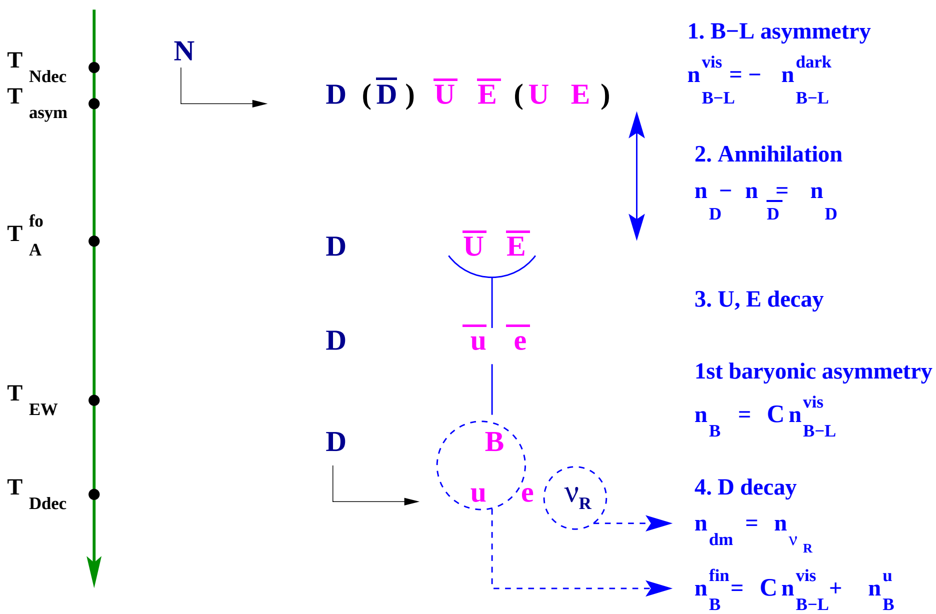

Figure 1: Steps of the Matter Genesis scenario

3.4 Summary of constraints

There are several constraints to put on scales and couplings for the above scenario to work. They are summarized in the present section.

First, the messenger particles D have to decay after EW symmetry breaking to protect the baryon number from erasure. Moreover, since the D decay products contributes to the baryon number, D decay should take place before nucleosynthesis. From this we get

$$h_d^5 \, v_R \;\gtrsim\; 10^{-21} \, TeV, \tag{5}$$

where h_d is the D Yukawa coupling. This is quite a nasty constraint, since it require a rather small Yukawa coupling to be satisfied.

Second, in order to get a ratio of baryon and dark matter number density of $\mathcal{O}(1)$, we require D to decay after the completion of $D - \bar{D}$ annihilation. This implies, using for the temperature of annihilation interactions freeze-out $T_A^{fo} = M_D/x_f$ ($x_f = \mathcal{O}(20)$ see [16]) :

$$h_d^{-3}\, v_R \;\gtrsim\; g_*^{-1/2} \times 10^{15} \;\; TeV. \tag{6}$$

Third, the D asymmetry produced in N decay must be larger than the $D-\bar{D}$ relic from freeze-out. Since D annihilates through strong interactions, using the same arguments than [10], we obtain :

$$h_d\, v_R \;\lesssim\; \left(\frac{3\, GeV}{m_{\nu_R}}\right) \times 10^4 \;\; TeV. \tag{7}$$

Finally, the abundance ν_R produced after reheating at T_{RH} must be negligible compared to the abundance from D decay. Assuming the ν_R are produced essentially through $SU(2)_R$ gauge bosons and taking $T_{RH} \gtrsim M_D$, we get

$$h_d^{-3}\, v_R \;\gtrsim 10^{23} \;\; TeV. \tag{8}$$

All together, these constraints yield a parameters space reduced to

$$10^7\, TeV \lesssim v_R \lesssim 10^{11}\, TeV \quad \text{and} \quad 10^{-7} \lesssim h_d \lesssim 10^{-5}. \tag{9}$$

This region is showed in Figure 2. There is a small but non-vanishing region where all the constraints can be met. In particular, the messenger D particles are rather light, with a mass $\mathcal{O}(TeV)$, compared to the scale of left-right symmetry breaking. This result is consistent with the results of Kitano and Low [10, 11].

4 Observational implications ?

Our dark matter candidate is, by construction, rather light $m_{\nu_R} \sim GeV$ and abundant. Its cross-section is, by necessity, very small. This is essentially because our right-handed neutrinos must be non-thermal relics, with nearly the same number density as baryons. We had to pay a heavy price to achieve this result. First, the discrete symmetry of our model is not particularly natural. Second, the Yukawa coupling of the messenger particle is quite small. Last, the mass of the dark matter candidate is fixed by hand.

On the observational side, we expect our right-handed neutrinos to be present in the core of the Galaxy where they could annihilate with each other producing a heavy Z_R boson, or be co-annihilated with right-handed quarks or leptons. Unfortunately the cross-section is way too small, $\sigma v \lesssim 10^{-32} pb$, to give any observable signal.[2] We expect this conclusion to be generic for dark matter

[2] By way of comparison, the cross-section needed to reach the sensitivity of INTEGRAL signals would be $\mathcal{O}(10 - 100 pb)$ for a dark matter candidate with mass of $\mathcal{O}(GeV)$ (see [17] for more details about the INTEGRAL signal and it's correlation with light dark matter annihilation).

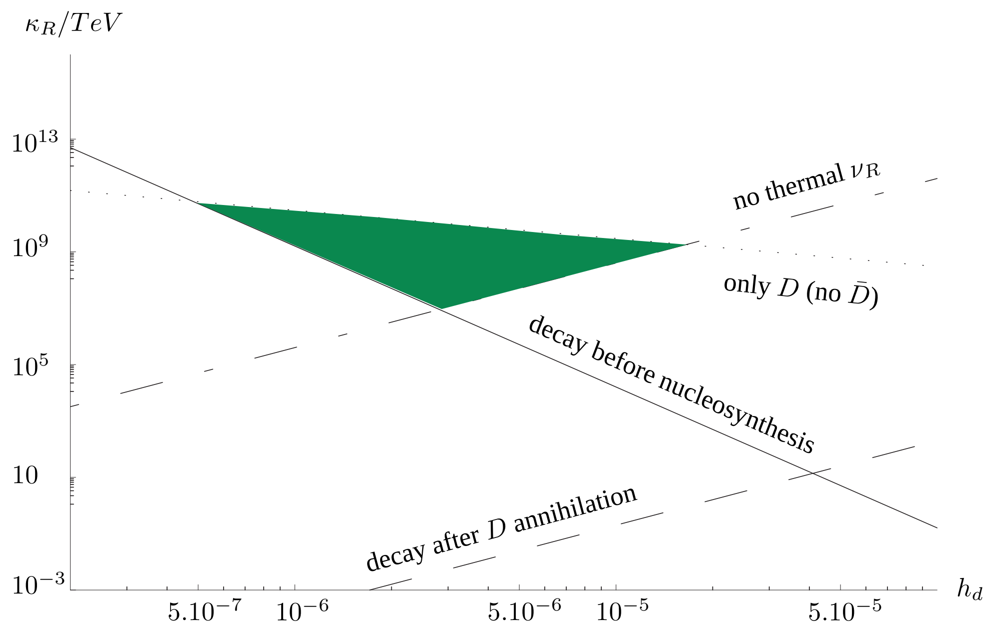

Figure 2: $\log(\kappa_R/TeV)$ *as a function of* $\log(h_d)$. *The different constraints : (5) line, (6) dashed, (8) dot-dashed (the excluded region is under these lines) and (7) dotted (the excluded region is over this line). The allowed region is in green.*

candidates related to the baryon asymmetry of the Universe, although we have no general proof.

Our dark matter candidate and the messenger have otherwise similar characteristics as in the model discussed in [11]. In particular, baring other explanations, light right-handed neutrinos might be of interest to explain the apparent suppression in the power spectrum on small scales, having a free-steaming length ~ 0.1 Mpc.

The only hope to detect something in our model is by the production at a collider of the strongly interacting messenger particle, analog to a very heavy quark. Our messenger has a mass range between 1 TeV and 10^6 TeV, corresponding to a life time between $10^2 s$ and $10^{-10} s$. As already underlined in [10], at least at the very lower part of this mass range, such a particle could be produced at the LHC.

5 Conclusion

We have discussed a mechanism of matter genesis, based on a left-right symmetric extension of the Standard Model, the basic idea being that both a baryonic and dark matter asymmetry have to be generated at some stage in the history of

the Universe. Our dark matter candidate is a stable right-handed neutrino with mass $\sim 3\,GeV$. The idea, which has been proposed by several authors, is quite attractive. However we found it quite difficult to realize. Although one should perhaps not try to draw a general conclusion from our model, the introduction of realistic gauge and Yukawa couplings shows that such a scenario is doomed to be very constrained.

This being said, the main drawback of the whole approach is still that such a candidate dark matter is essentially undetectable. On the theoretical side, we should also pause and ask what has been gained. We have a very contrived model, with a discrete symmetry, many new degrees of freedom and new interactions and yet all we can do is to relate the baryon and dark matter particle densities. The mass of the dark matter particle has still be fixed by hand.

By way of conclusion we would like to mention a recent attempt which could confront this difficulty. This mechanism could arise in the context of scalar-tensor theories of gravity coupled to matter. Since the mass of matter fields depends generically on the *vev* of a scalar field, the presence of matter induces an effective potential. For concreteness, suppose that the coupling of φ to matter is such that

$$V(\varphi) = m_b e^{\alpha\varphi} n_b + m_{dm} e^{-\beta\varphi} n_{dm},$$

with $\alpha, \beta > 0$. Then

$$\Omega_b/\Omega_{dm} = \beta/\alpha \tag{10}$$

at the minimum of the potential (which depends on the density of ordinary and dark matter). If the couplings are of the same order, one gets a dynamical relaxation of the ratio (1). This idea is all nice and well, but again poses problems of its own. Baryons masses are varying, there is an extremely light scalar field with gravitational coupling, etc. The authors in [18] have proposed to add an extra potential term to cure these issues (φ then behaves as a chameleon, changing mass in function of its environment) but the potential needs some fine tuning so as not to ruin (10). This model is thus not very satisfying but the idea is seductive. At any rate, explaining the apparent coincidence of (1) is a challenge worth pursuing.

Acknowledgments

We thank Fu-Sin Ling, Emmanuel Nezri and Jean-Marie Frère for helpful discussions. This work is supported in part by IISN, la Communauté Française de Belgique (ARC), and the belgian federal government (IUAP-V/27).

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